# CCPC Phase V Final Report

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## Executive Summary:

This document describes the studies the Canadian Clean Power Coalition (CCPC) completed or was involved in during Phase V of its work. The following shows highlights of each study. Economic summary reports for most studies listed below have been provided separately. The reports completed by Jacobs, with the assistance of other entities, have been provided to CCPC Participants over the course of Phase V. Some of the technologies described below are in an early stage of development. Each of the numbered items below corresponds to the number for a study described in further detail at the end of this executive summary.

1. Greenfield Coal with Low GHG Emissions: This study evaluated several novel ways to produce power utilizing coal as a fuel in a new Alberta facility while limiting the GHG emission intensity of all cases to less than .42 t $CO_2$/MWh.

    - The open Brayton cycle technology based on the Allam Cycle (.07 t CO2/MWh) had the lowest estimated first year cost of power of $131/MWh.
    - A supercritical coal plant with partial amine $CO_2$ capture (.42t $CO_2$/MWh), had the next lowest cost at $172/MWh.
    - The Oxy-PFBC plant (.11 t $CO_2$/MWh) is estimated to have a higher first year power cost than either of the two cases described above. This was an unexpected outcome.
    - While these power costs are significantly greater than the cost of a new NGCC ($60/MWh), further work should be completed on the open Brayton cycle and the Oxy-PFBC technologies to optimize them and refine their costs.

2. Fuel Cell Repowering: A molten carbonate fuel cell was designed to capture $CO_2$ and make power on the Lingan power plant in Nova Scotia.

    - A coal plant retrofitted with these fuel cells was estimated to have a similar power cost as the underlying coal plant without CCS and was estimated to have a power cost 10% greater than an NGCC in Nova Scotia.
    - For Alberta the power costs for a molten carbonate fuel cell CCS system were significantly lower than amine scrubbing CCS but about 20% greater than the cost for a new NGCC.
    - The capital and operating cost for this technology were updated for the repowering study and the costs for this study may no longer be valid.

- This is clearly a promising technology and further work should be completed to pilot the technology on coal fuel gas.

3. NOx and $SO_2$ Emission Reduction Study: Four sets of newer NOx and $SO_2$ control technologies for three coal plants were costed by EPRI.

   - The increase in the cost of power to meet expected NOx and $SO_2$ limits ranged between $18 and $27/MWh for Alberta plant.
   - The increase in the cost of power to meet expected NOx and $SO_2$ limits ranged between $33 and $61/MWh for Saskatchewan plant.
   - The increase in the cost of power to meet expected NOx and $SO_2$ limits ranged between $34 and $96/MWh for Nova Scotia plant.
   - None of the configurations became more attractive when the amortization period changed from 30 to 10 years.

4. Cycling of Coal Plants: EPRI staff completed a one day seminar on the impact of cycling coal plants more often to support the adoption of renewable power.

   - Cycling of coal plants causes numerous forms of damage to many plant components. EPRI identified issues to monitor and provided mitigation suggestions.
   - EPRI is studying many impacts of cycling on coal plants to assess how to manage them and the costs to maintain the plants.
   - The costs range from increased routine maintenance, early replacement of components, component failures, safety concerns, reduced performance, earlier retirement dates, etc.

5. IHI Oxy-fuel Retrofit: The CCPC worked with a consortium led by IHI to evaluate the costs to retrofit a coal plant in Alberta to oxy-fuel with CCS.

   - The costs to retrofit a coal plant with oxy-fuel may be comparable to a new NGCC and may be lower than amine scrubbing CCS. However, many of the opportunities to optimize the economics of oxy-fuel were tied to dates and unclear provisions of the Federal government coal regulations. IHI completed a second phase of the study. Given the regulations are unclear and the time is insufficient to meet the dates specified in the regulations, oxy-fuel has not been pursued further in Alberta.

6. Natural Gas Generation with Low GHG Emissions: Eight technologies were evaluated to produce power from natural gas with an emission intensity of about .2 t $CO_2$/MWh.

   - Both amine scrubbing and molten carbonate fuel cell cases had first year power costs of about $67/MWh. This is about 20% greater than the cost for a new NGCC at $56/MWh.
   - The open Brayton cycle based on the Allam cycle was estimated to have a much higher first year cost than the cases above (even when normalized for capture rate), an unexpected outcome.

- The cases using an autothermal reformer to produce a low carbon fuel and calcium looping had first year cost of power ranging from $83 to $86/MWh.
- Further piloting work on molten carbonate fuel cells should and is being completed.

7. Biomass Co-firing: The CCPC updated its costs estimates for biomass co-firing to meet an emission intensity of .42 t $CO_2$/MWh at various capacity factors.

    - Alberta and Nova Scotia may have half a dozen forms of biomass which, when co-fired, lead to an overall first year cost of power less than building a new NGCC or peaker, particularly at lower capacity factors. Alberta supply is likely sufficient to mitigate more than 1 Mt $CO_2$/yr.
    - Saskatchewan may only have a few forms of biomass which, when co-fired, lead to an overall first year cost of power less than building a new NGCC or peaker. The number increase as the capacity factor decreases.
    - More co-firing tests are required to understand plant performance. Regulations and incentives similar to other forms of renewable energy will be required to support the adoption of biomass co-firing.

8. Repowering: Eleven options to repower coal plants, with an emission intensity of .42 t $CO_2$/MWh, were compared to the cost of building a new NGCC.

    - The power cost for replacing the furnace with a gas turbine and HRSG suppling steam to the existing steam turbines, was similar the cost of power from a new NGCC.
    - The next two most promising technologies were biomass co-firing and molten carbonate fuel cells. These were forecasted to have slightly lower power costs than the best amine scrubbing case utilizing a large gas turbine and HRSG to provide steam and power to the CCS system and the grid.
    - Solid oxide fuel cell costs and operating life need to improve to make this an attractive option.
    - Further work to pilot biomass co-firing and molten carbonate fuel cells should be pursued.

9. Coal to Gas Conversion: This study looked at the emission intensity of three plants at full, part and min load and estimated the costs to complete the conversion from coal to gas fuel.

    - At max and part load the heat rate of the plant on gas is expected to be lower than fired on coal at similar output. The heat rate will be quite high at min load. The GHG emission intensity will be about .05t $CO_2$/GJ X heat rate.
    - The capital cost to complete the conversion only will likely be less than $60 million. Firing on gas will however reduce the output of the plant. Depending upon the plant only some of the modifications to increase output may be cost effective.
    - In Alberta the required selling price of power for a converted plant should be less than an NGCC. For Saskatchewan it may be a bit higher than an NGCC and in Nova Scotia where gas prices are quite high, the price will be materially higher than that for an NGCC.
    - Depending upon availability and price, biomass could be fired to reduced GHG emissions below an intensity of 0.42 t $CO_2$/MWh and that doing so may help increase plant output.

- At full output, the plants studied had an emission intensity of about .6 t $CO_2$/MWh.

10. Oxy-PFBC Test Fire: The CCPC has committed about $180,000 to test fire Canadian coals at the CanmetENERGY facility in Ottawa. This work will be completed in 2018.

11. CanmetENERGY Task Share: CanmetENERGY completed several study projects during Phase V which were of interest to the CCPC.

    1. Entrained flow gasification - Reactor network models predicting the performance of entrained flow slagging gasifiers that were developed as part of this work were able to well represent gasifier operation whereas equilibrium based models that are often used in techno-economic analyses were not able to represent the gasifier adequately. The reactor network models were validated through pilot plant operations firing petroleum coke from the Canadian oil sands. The reduced computational effort of the reactor network models compared to computational fluid dynamics models permitted transient gasifier load following studies and failure mode studies to be completed quickly.
    2. Gasification and combustion - The oxidation states of vanadium in ashes produced by the combustion and gasification of Canadian petroleum coke was determined enhancing our ability to understand the effects of oil sands derived ashes on various processes.
    3. Calcium looping for post-combustion CO2 capture – there are a number of methods intended to enhance the performance of calcium sorbent for CO2 capture via calcium looping, however, based on pilot plant test work it appears that minimal modification of the calcium sorbent will be the most economically attractive approach.
    4. Chemical looping combustion – Performing chemical looping combustion at elevated pressures increases the attractiveness of low cost, environmentally benign oxygen carriers. The optimum pressure for chemical looping combustion may be in the range of 3 to 7 bar.